The Cosmic Ray Key Science Project

Status Report, LSM 23-11-16

Jörg P. Rachen for the

LOFAR Cosmic Ray Key Science Project

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Radboud University

ASTRON

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Vrije Universiteit Brussel

Journal papers published:

Schellart+, **A&A 560, A98 (2013): Detecting cosmic rays with the LOFAR radio telescope**

Schellart+, **NIMPA 742, 115 (2014): Recent results** from cosmic-ray measurements with LOFAR

Schellart+, **JCAP 10, 014 (2014): Polarized radio emission** from extensive air showers measured with LOFAR

Buitink+, **PRD 90, 082003 (2014):** Method for **high precision reconstruction of air shower X_{max}** using two-dimensional radio intensity profiles

Thoudam+, **NIMPA 767, 339 (2014): LORA** – A **scintillator array for LOFAR** to measure extensive air showers

Nelles+, **APh 60, 13 (2015):** A parameterization for the radio emission of air showers as predicted by **CoREAS simulations** and **applied to LOFAR measurements**

Corstanje+, **APh 61, 22 (2015):** The **shape of the radio wavefront** of extensive air showers as measured with LOFAR

Schellart+, **PRL 114, 165001 (2015): Probing Atmospheric Electric Fields in Thunderstorms** through Radio Emission from Cosmic-Ray-Induced Air Showers

Nelles+, **APh 65, 11 (2015):** Measuring a **Cherenkov ring in the radio emission** from air showers **at 110-190 MHz** with LOFAR

Nelles+, **JCAP 5, 018 (2015):** The **radio emission pattern of air showers** as measured with LOFAR – a tool for the reconstruction of the energy and the shower maximum

Nelles+, **JInst 10, 1005 (2015): Calibrating the absolute amplitude scale** for air showers measured at LOFAR.

Thoudam+, **Aph 73, 34 (2016): Measurement of the cosmic-ray energy spectrum** above 10^{16} eV **with the LOFAR Radboud Air Shower Array**.

Corstanje+, **A&A 590, 41 (2016): Timing calibration** and spectral cleaning of LOFAR time series data.

Buitink+, **Nature 531, 70 (2016):** Radio detections of cosmic rays reveal a **strong light mass component at 10^{17} – $10^{17.5}$ eV**.

Trinh+, **PRD 93, 023003 (2016):** Influence of **Atmospheric Electric Fields** on Radio-wave Emission from Cosmic-Ray Induced Air Showers.

Papers in the queue:

Scholten+: Measurement of the **circular polarization in radio emission from extensive air showers** confirms emission mechanisms. **Accepted for PRD**

Corstanje+: The **effect of the atmospheric refractive index** on radio detection of extensive air showers. **In revision after 1st referee report**

Trinh+: **Circular polarization** of radio emission from extensive air shower probes **atmospheric electric fields in thunderstorm conditions**. **In preparation**

Rossetto+: **Frequency spectrum analysis of radio emission from extensive air showers. Coming next.**

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Stokes parameters

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

The intensity

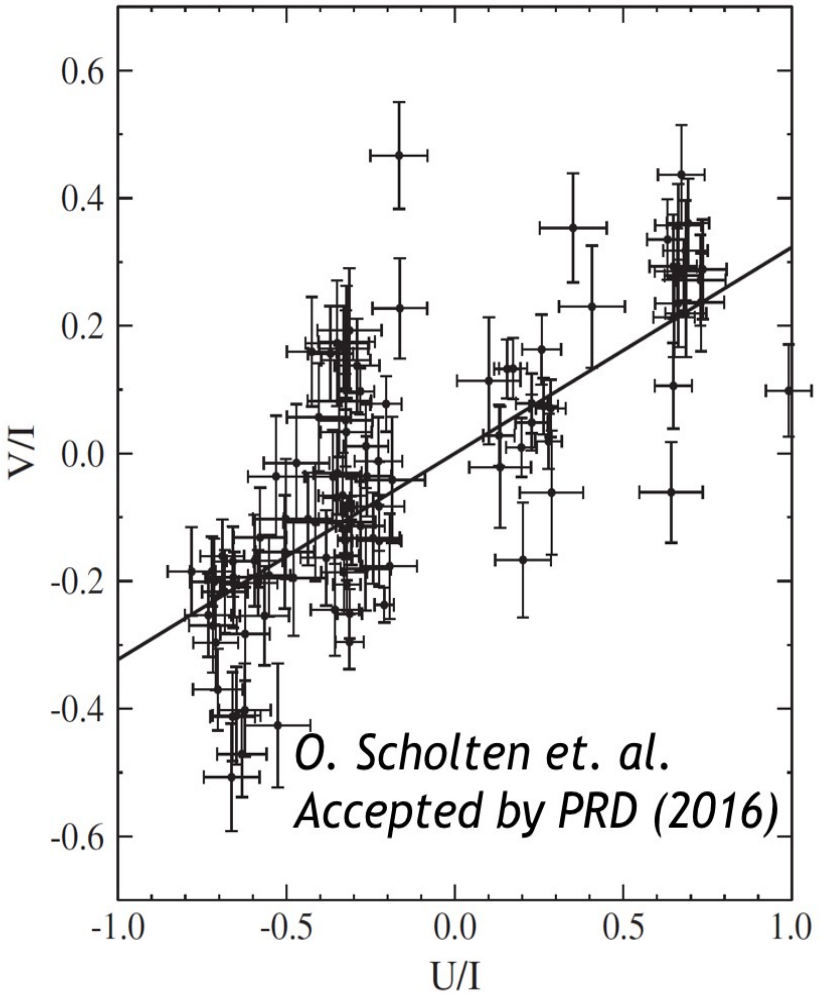
The linear polarization:

$$\alpha = \frac{1}{2} tan^{-1}\left(\frac{U}{Q}\right)$$

The circular polarization.

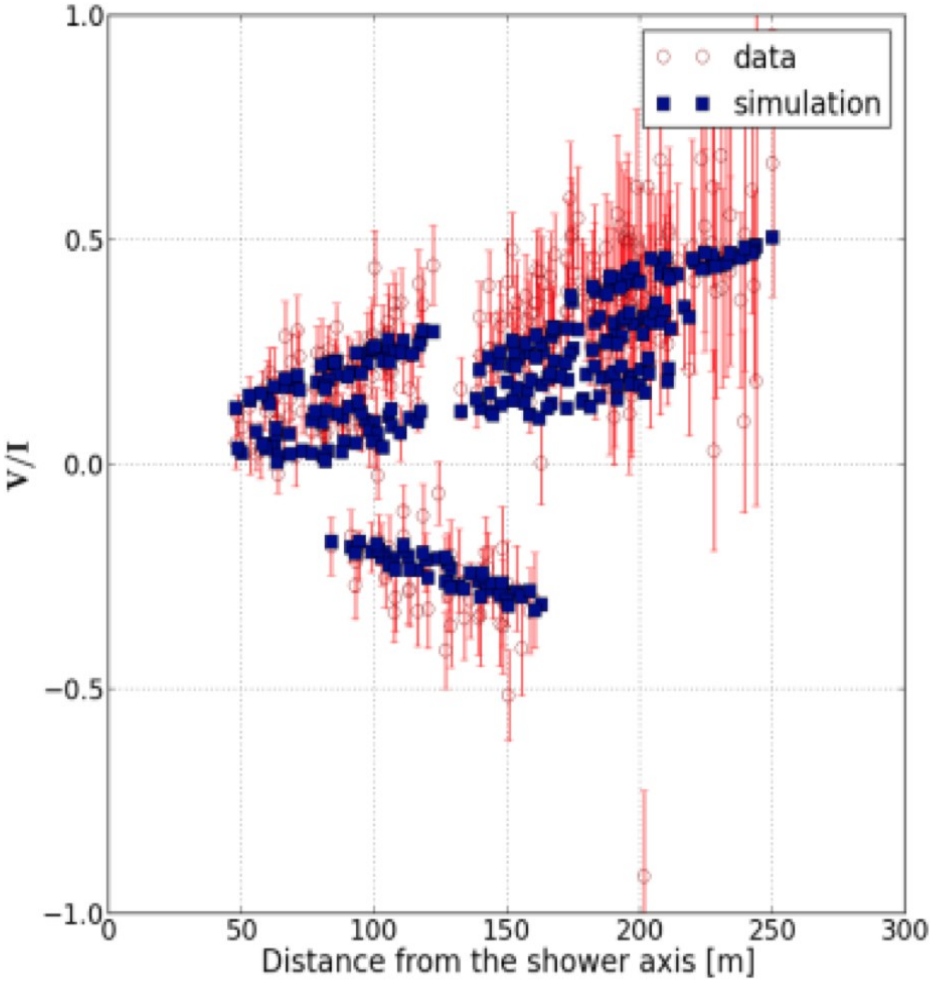
Fitting Stokes parameters means fitting intensity, linear polarization and circular polarization

Fair-weather showers



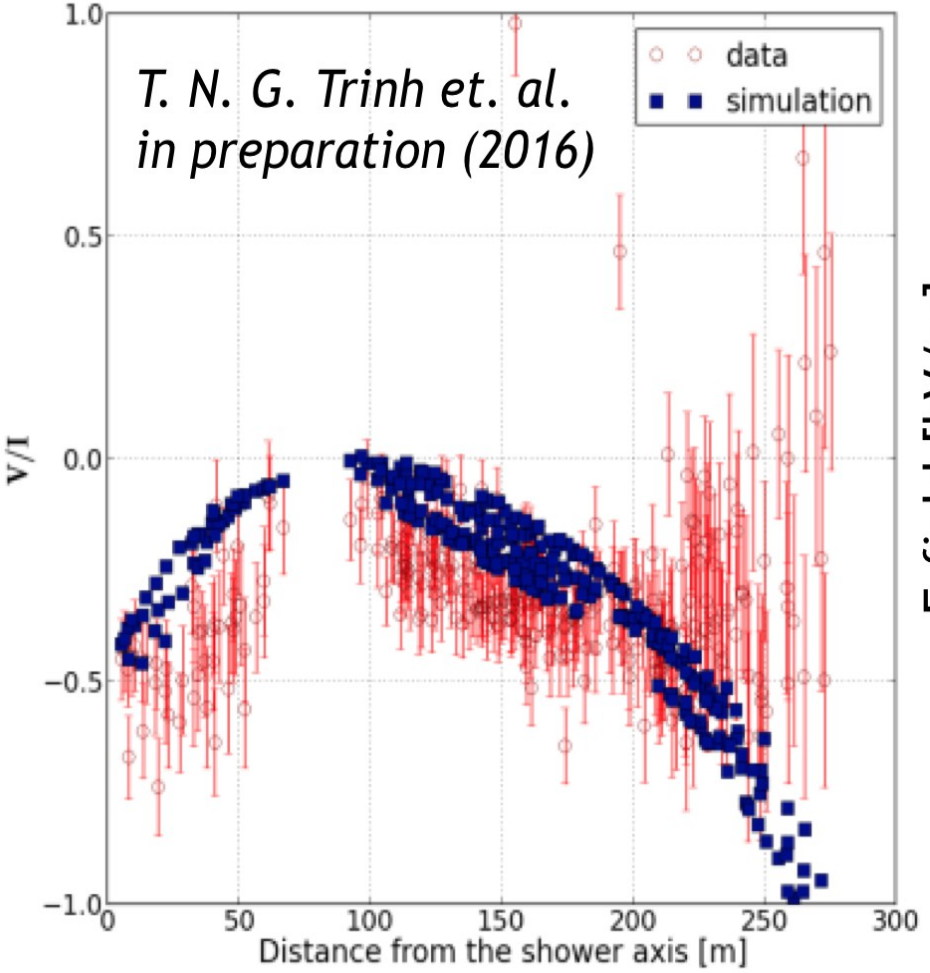
90 m < d < 100 m, |cos Φ| < 0.5

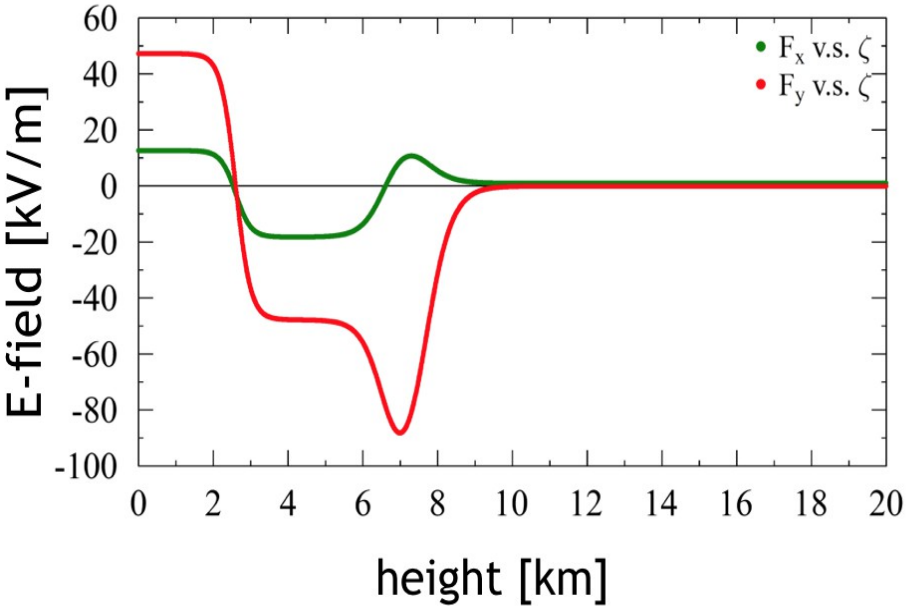
The line: V/U = 0.32 → time delay for charge-excess: 1 ns



Measured and simulated circular polarization of a single event

Thunderstorm showers





Measured and simulated circular polarization of a single event

Large circular polarization near the core, due to change in transverse current caused by the change of E-fields.

Further CRKSP projects:

- **Effect of atmospheric refractive index**
  - Changes the Čerenkov angle of radio pulse
  - Depends on weather conditions (i.p. humidity)
  - Produces an average shift in X_{max} (towards heavier composition)
  - Considering it for actual weather conditions will reduce systematic errors

- **Frequency spectrum analysis**
  - Radio spectrum is strongly dependent on distance from shower axis
  - Also dependent on X_{max}
  - Can be used to further constrain shower properties → reduce errors

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- **Frequency spectrum analysis**
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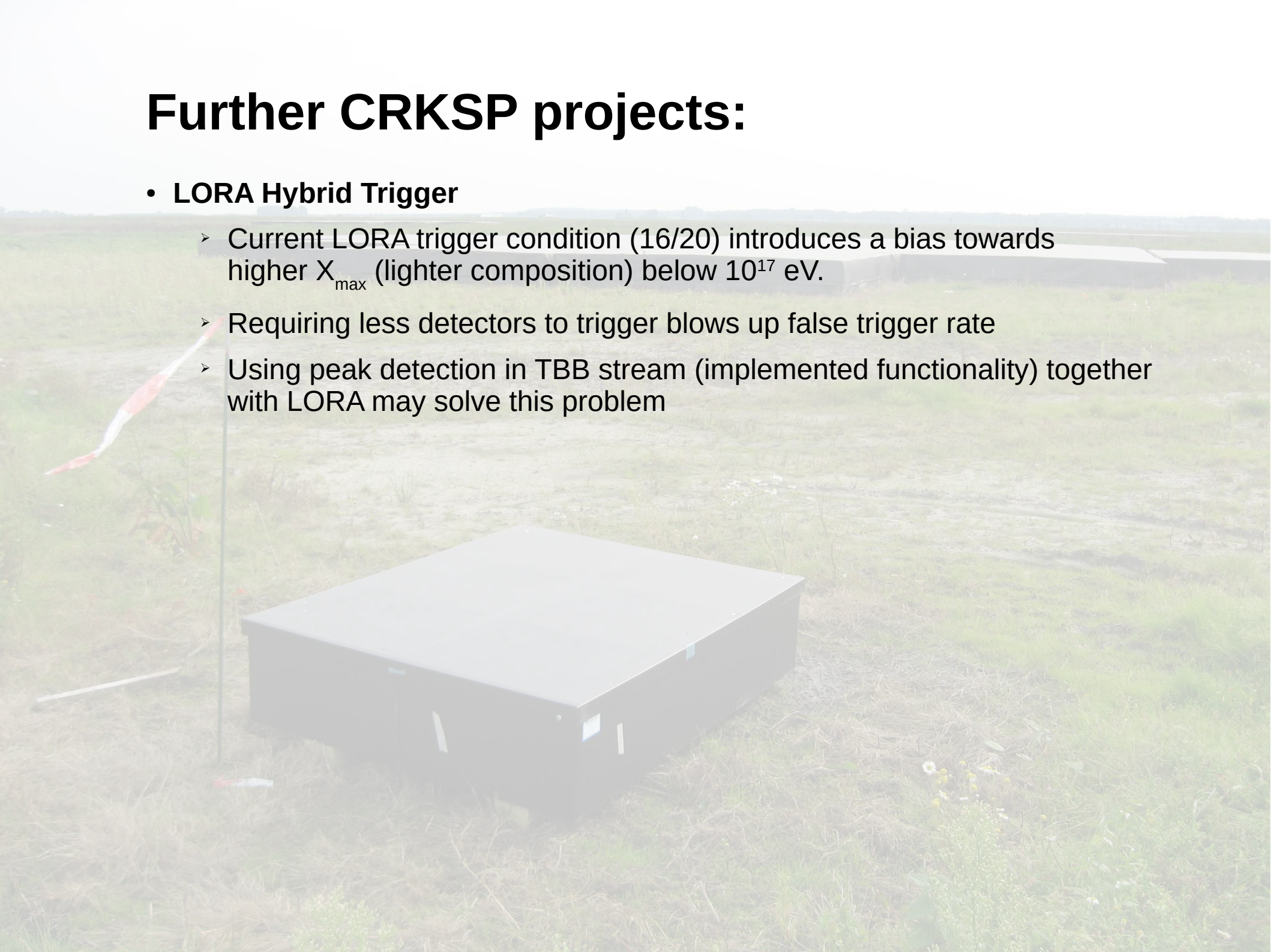
- **Will move LOFAR towards the most accurate experiment determining X_{max}**

Further CRKSP projects:

- **LORA Hybrid Trigger**
  - Current LORA trigger condition (16/20) introduces a bias towards higher X_{max} (lighter composition) below 10^{17} eV.
  - Requiring less detectors to trigger blows up false trigger rate
  - Using peak detection in TBB stream (implemented functionality) together with LORA may solve this problem



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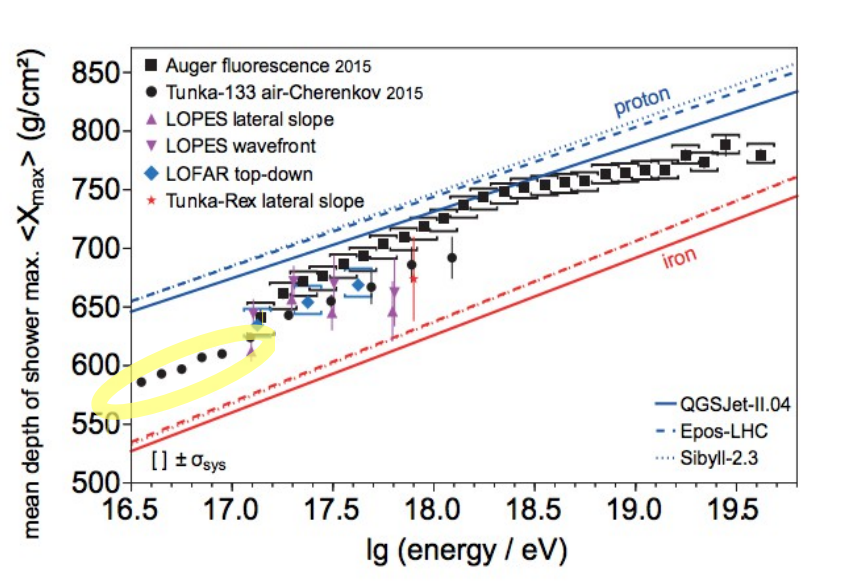


- **Will move LOFAR towards lower energies, 10^{16}-10^{17} eV, difficult for other experiments and detection methods**
- **Complementary to self trigger studies → test observation proposal in preparation**

Further CRKSP projects:

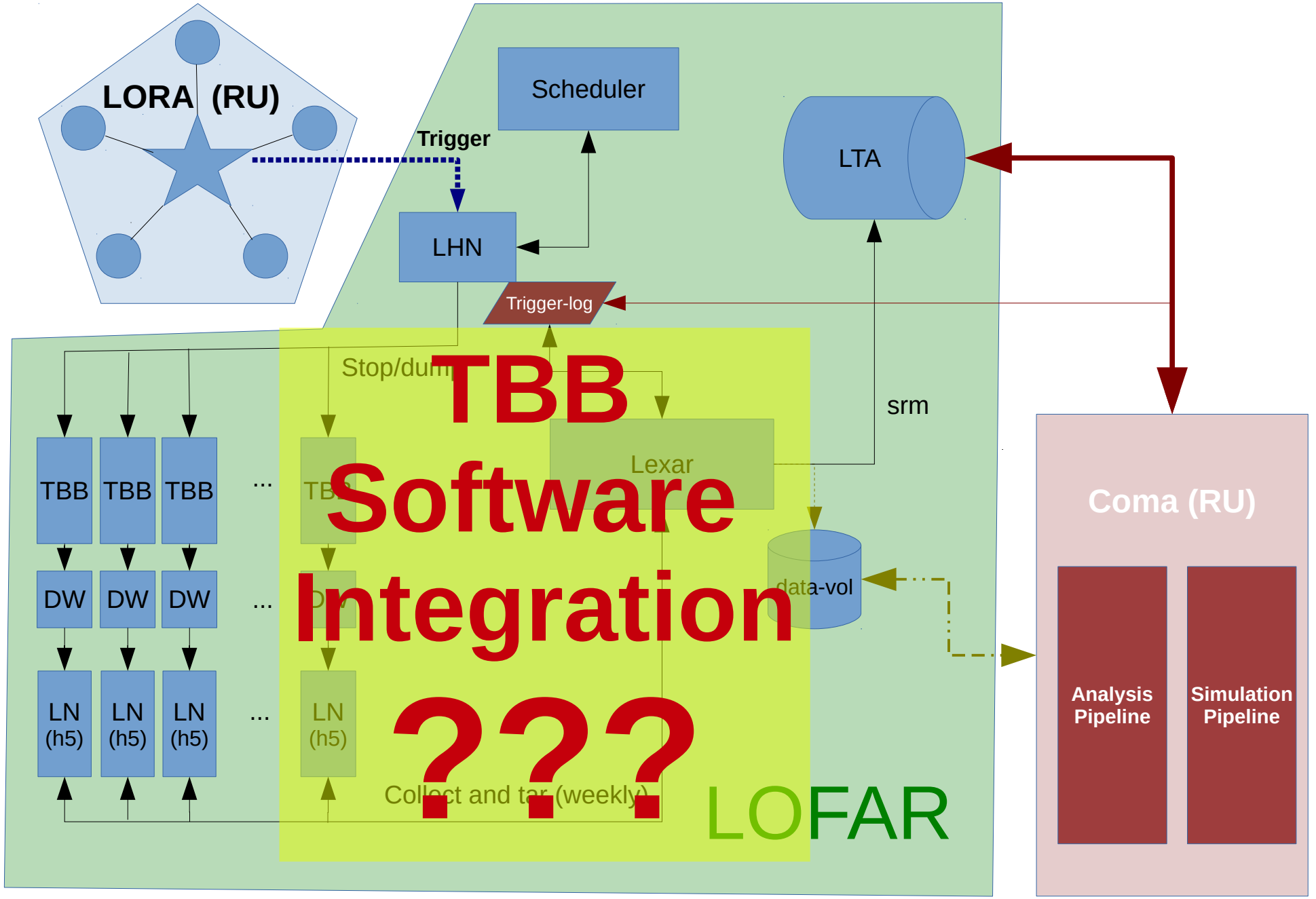
- **NuMoon – radio pulses from ZeV neutrinos from the moon**
  - Search for radio pulses from particles >10^{21} eV hitting the moon
    → energies not doable by cosmic accelerators, do they exist?
  - Multibeam observations of the moon with nanosecond time resolution in real time
  - Uning DRAGNET (GPU cluster of the LOFAR pulsar group) for PPF inversion (in real time, to trigger TBBs)
  - Status: software prototype developed, can do simulations
  - Plan: Propose O(10) test observations of the moon, ~10 seconds each with subsequent dump of TBBs (real time signal)

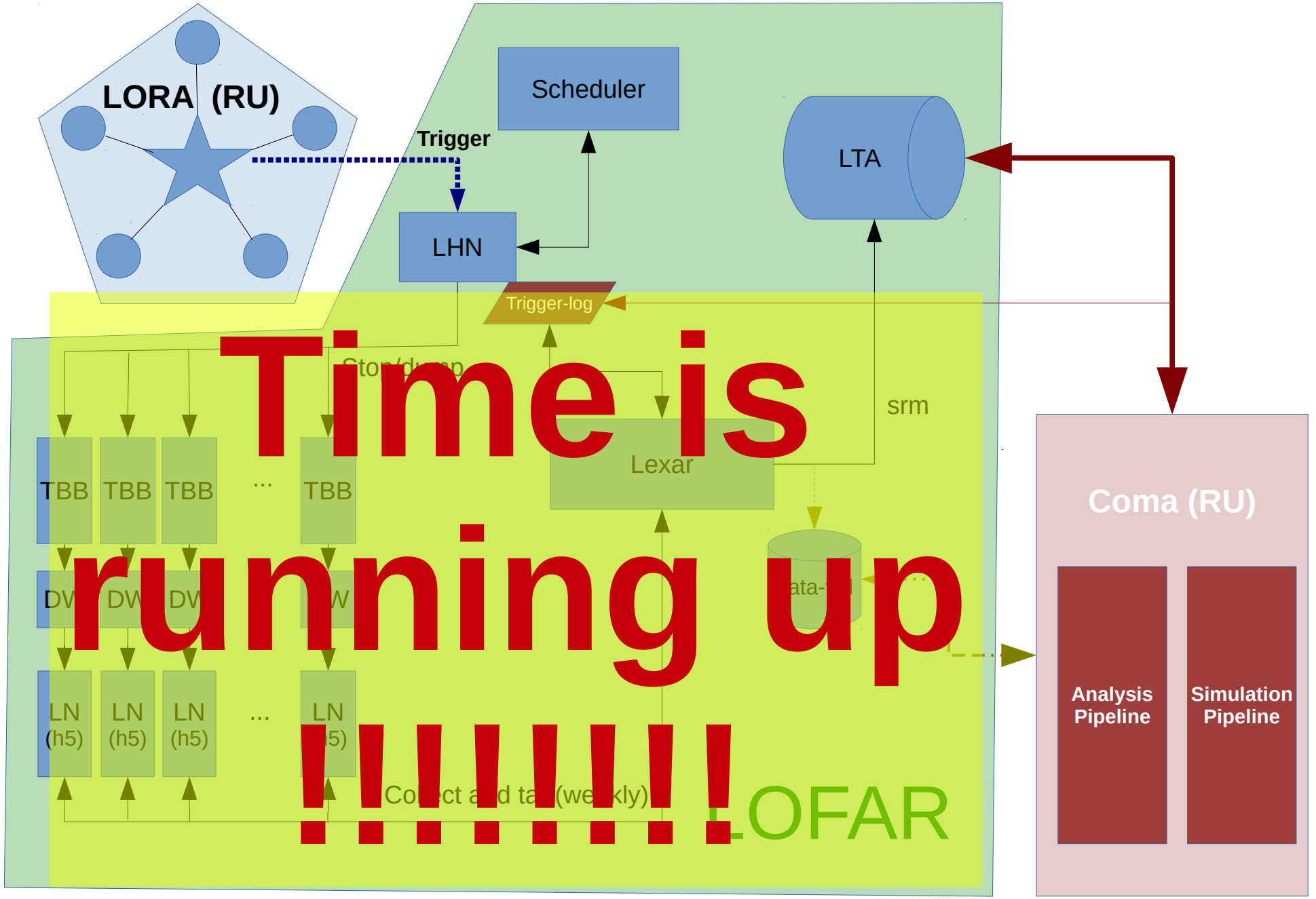
    (proposal needed?)

Further CRKSP projects:

- **NuMoon – radio pulses from ZeV neutrinos from the moon**
  - Search for particles >10^{21} eV, not doable by cosmic accelerators
    → **New Physics** (topological defects, parallel universes, …)
  - Multibeam observations of the moon with nanosecond time resolution in real time
  - Uning DRAGNET (GPU cluster of the LOFAR pulsar group) for PPF inversion
  - Status: software prototype developed, can do simulations
  - Plan: Propose O(10) test observations of the moon, ~10 seconds each with subsequent dump of TBBs (real time signal)

- **Will move LOFAR towards highest, yet unexplored energies**


LORA (RU)
Trigger
Scheduler
LTA
LHN
Trigger-log
Stop/dump
srm
Lexar
TBB
TBB
TBB
...
TBB
DW
DW
DW
...
DW
LN
(h5)
LN
(h5)
LN
(h5)
...
LN
(h5)
data-vol
Coma (RU)
Analysis Pipeline
Simulation Pipeline
TBB Software Integration ???
Collect and tar (weekly)
LOFAR


LORA (RU)
Trigger
Scheduler
LHN
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srm
Lexar
TBB
TBB
TBB
...
TBB
DW
DW
DW
W
LN
(h5)
LN
(h5)
LN
(h5)
...
LN
5)
Coma (RU)
Analysis
Pipeline
Simulation
Pipeline
LOFAR
Time is
running up
!!!!!!!!